

# THE RAILWAY OPERATION PROCESS EVALUATION METHOD IN TERMS OF RESILIENCE ANALYSIS

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## Abstract:

*In complex socio-technical systems there is an influence of safe unwanted events on the occurrence of accidents. It is like domino bricks. Therefore, it is not only the recovery from major events that is important, but also the recovery from disruptions in operation. As the literature review shows, the recovery of operation processes is analysed by single criteria for small disruptions. On the other hand, resilience research is focused on the network and major events, but not on frequent small-consequence events that affect operational processes. The performance of a system is a key parameter when evaluating resilience. As a result of the performed literature survey, the aim of the paper was to propose a new method for evaluating performance in terms of operational processes and resilience analysis. Moreover, it is also important to order the most important terms related to this issue, as well as to introduce new types of qualities, which are not only focused on the system, but also on the implemented operational processes.*

*The paper consists of eight sections. The introduction section describes generally the problem, that leads to formulation of the aim of the paper and description of its structure. It is followed by the second section consisting of a complex literature survey. Section three orders the reliability, robustness and resilience definitions. Section four analyses the performance influencing factors using Fault and Event Tree Analysis, while section five defines the operational layer of the system and shows a formal description of operation processes. Section six presents the operation process evaluation model. It was elaborated using the Fuzzy Logic approach, that allows combining of incoherent system and process qualities: punctuality, probability no further delays, quantitative implementation of scheduled processes, reconfiguration level. Afterwards a case study is shown to present the method application. The performed case study shows the advantages of the proposed approach, which is related to the most common methods. The paper ends with conclusions and further research perspectives.*

**Keywords:** railway, resilience, performance, Fuzzy Logic

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## 1. Introduction

The railway transport system can be defined by diverse qualities. The most common general qualities were identified by Jacyna in 2009 as: the railway network, rolling stock, the timetable, passengers and freight. The timetable is related to all of these issues and creates the relation between the network and rolling stock. It includes boundaries, and it should be adequate to fulfil market demand. Boundaries are interpreted as the relationship between systems with respect to their states (Johansson and Hassel, 2010). Models normally take into account arc capacities in order to describe the performance of the rail system (Johansson and Hassel, 2010). The most undesirable events in the rail system result in delays. About 98% of all unwanted events in the rail system end in so-called safe consequences (Restel et al., 2019), and there is therefore no further investigation.

Nevertheless, there is an influence of safe unwanted events on the occurrence of accidents. It is like domino bricks. Thus, it is not only the recovery from major events that is important, but also the recovery from disruptions in operation. These issues are typically not taken into account during the evaluation of resilience. Improving disruption recoverability can be a key factor in accident prevention. During previous researches, it was proven that small consequence events definitely have an influence on the occurrence of accidents (Restel, 2014).

It can be stated that it is not enough to keep the correct capacity of system branches, but it is also necessary to maintain the process schedule. Thus, the need arises to go beside the classic approach focussed on the network (system) resilience. The concept of operational resilience can fill the existing gap. Foster et al., (2019) stated that such an approach will be helpful in decision-making for adaptation processes. Patriarca et al. (2018) concluded from their performed literature review that the creation of simple and universal methods for the assessment of resilience is not possible for different types of complex sociotechnical systems. Therefore, the aim of the paper is to propose a method for evaluating the operation process as a part of further resilience investigation. More detailed goals are presented after the literature research. The paper contains eight sections, including the introduction and conclusions. The literature review shows the gap which will be filled by this contribution, as well as the starting level in terms of approaches and concepts. It is followed by

an ordered description of resilience and robustness concepts, and also an analysis of performance influencing factors. Then, a description of both the operation process and the model is followed by a case study. The conclusions highlight the most important issues and summarize plans for further research.

## 2. Literature research

Articles referring to timetable issues and its evaluation are focussed on disturbances. Unfortunately, the sources and impact of disturbances of diverse types of failures are not classified (Kroon et al., 2007, Solinen, 2017). The evaluation of system operation uses diverse indicators for finding the best alternative for dispatching. Waiting times and arc capacities are mainly used for evaluating timetable stability and efficiency (Buchel and Corman, 2018, Pächl, 2016). The evaluation of reconfiguration scenarios and strategies results in the finding of the best solution in terms of a given goal function. The given approaches are mainly based on only one evaluation criterion (Andersson et al., 2013, Louwerse and Huisman, 2014), however, the consequences of reconfiguration are not taken into account.

A lot of effort has been put into diverse optimization models (Jacyna and Golebiowski, 2015). Their development was focussed on supporting the decision making process after the occurrence of disruption. Literature reviews on this subject were performed by Yang et al. (2016). Railway problems are treated separately by various authors. For example, there are separate views on the timetable (Yang et al., 2014), the optimization of train movement (Yang et al., 2012), or risk management (Azad et al., 2016). Therefore, solutions to the problems are limited by a given perspective. The optimization criteria are therefore rather limited and one dimensional e.g. energy consumption (Yang et al., 2016, Urbaniak et al., 2019) or the travel time in a given network (Al Khaled et al., 2011). On the other hand, models that use more than one parameter for solving railway problems can also be found (Wang et al., 2015, Jacyna and Golebiowski, 2016). These approaches are dedicated to undisturbed operation. Moreover, they are mainly focussed on network capacity or energy consumption.

Robustness is a quality related to withstanding against undesired influences. It is described in a couple of different ways, which both differ in terms of

meaning. Robustness is known as the ability of a human-technical system to withstand inaccuracies (Salido et al., 2008). It can also be the system's ability to withstand trouble with no significant changes in the operation processes (Takeuchi and Tomii, 2005). Policella (2005) understands it as tolerance for undesirable events. However, the later on robustness is defined in terms of recovery time.

Dewilde et al. (2011) use robustness to assess timetables. It is defined as the ability of minimizing passenger travel times if small disruptions occur. The assumption was also made that the delays and recovery times are limited by fixed maximum values. Schobel and Kratz (2009) quantify robustness using the maximum value of primary delays that will not affect any passenger transfers. Goverde (2007) sees timetables as stable if delays do not propagate between assumed time periods. Goverde (2008) also introduces locally or globally stable systems. Stability means that primary delays have to be compensated in a finite time (Andersson et al., 2013).

Timetables can also be called robust if disruptions do not create delays (Kroon et al., 2008b). Moreover, the timetable will also be seen as robust if initial delays will be made up for as fast as possible, if the number of secondary delays is very small, and if almost no dispatcher actions are necessary to recover the system operation. Dispatcher operations were analysed by Lu et al. (2017). Departure time, the possibility of overtaking, train order changes, and time reserves were determined as decision variables for the management of the system after disruptions. It can be seen that the operation process cannot be secured in terms of disruptions. Therefore, an adaptation was introduced by Foster et al. (2019), which is defined as the ability of systems to self-organize and meet the demands caused by disruptions. The approach, which explains failure mechanisms and their propagation, as well as concepts for recovery, is called Resilience Engineering (Patriarca et al., 2018).

Regarding Ouyang et al. (2019), it can be concluded that robustness is focussed on pre-event issues, while resilience is focussed on the minimization of undesirable event consequences. In resilience research, recovery from disruptions is associated with system repairs (Zhang et al., 2018), and not necessarily process management. Recovery process modelling is also the subject of diverse research works (Cassottana et al., 2019).

Resilience evaluation is focussed on disasters, large scale events, and the recovery of the system from their consequences (Hosseini et al., 2016, Rus et al., 2018, Liu and Song, 2020). Based on U.S. government documents, Zhang (2018) defines resilience as "the ability to prepare for and adapt to changing conditions and the ability to withstand and recover rapidly from disruptions". Similar to robustness research, in resilience oriented papers there is also confusion regarding these two qualities (Alipour and Shafei, 2016, Cox et al., 2011). Many contributions limit resilience to recovery until a stable system state is reached (Tang and Heinemann, 2018, Christodoulou et al., 2018). The level of system function is defined in the literature differently, and the term resilience is sometimes mixed with performance (Hosseini et al., 2016). Performance gives information about the ability of a system to implement desired tasks. It can be defined as (Knudsen et al., 2012):

- monitoring of the system,
- handling early warning deviations,
- reacting to deviations,
- learning.

The importance level of using performance indicators depends on the utilised resilience approach. Hosseini et al. (2016) identified four main groups of approaches:

- conceptual frameworks,
- semi-quantitative indices,
- structural-based models,
- general measures.

The first two categories are based on qualitative methods. Therefore, a detailed performance evaluation is not a part of that research. One of the used approaches is the qualitative Functional Resonance Analysis Method (Patriarca et al., 2018). The basic concept of evaluating performance for resilience quantification is based on the comparison of work as done with the work as imagined (Patriarca et al., 2018). Structural-based models consist of optimization, simulation, and fuzzy logic models.

Looking at (Hosseini et al., 2016, Rus et al., 2018, Liu and Song, 2020), it can be stated that about thirty percent of measures do not take into account the performance function. The remaining ones refer to average performance for a given time interval, or in a function of time, and are related to the kept performance level after disruptions. It was found that performance is described mainly in one dimension. Approaches that take into account more dimensions

tend to assess resilience separately for each of them. The relevance of quantitative resilience assessment in reference to system performance is still increasing (Xu et al., 2020).

A literature survey was made to find the most common parameters that describe the system and processes. After a general literature search, more than twenty papers connected to the investigation of resilience and performance were selected for a more detailed analysis.

Typically, only one dimension (one parameter) is taken into account for performance quantification. The most common performance parameters are:

- time (Hong et al., 2019, Lu et al., 2017, Do and Jung, 2018),
- capacity (Balal et al., 2019, Kierzkowski and Kisiel, 2017, Dessavre et al., 2016),
- number of node connections (Ouyang et al., 2015, Pitilakis et al., 2016, Ramirez-Marquez et al., 2018).

The most commonly used technique for investigating resilience with respect to performance is simulation modelling (Zou and Chen, 2019, Argyroudis et al., 2020, Jacyna et al., 2014, Ramirez-Marquez et al., 2018, Jacyna and Zak, 2016). Fuzzy logic is also used, but less often. Moreover, its utilisation is limited to general factor evaluation, and not directly to performance evaluation (Bukowski, 2016, Edjossan-Sossou et al., 2020). Research that does not focus on resilience may use fuzzy logic for evaluating performance, as was the case with Kierzkowski and Kisiel (2017).

The analysed papers deal mainly with network performance in general and are related to major events. Some papers referring to process resilience can also be found. Nevertheless, they are related to chemical processes in plants (Jain et al., 2018, Jain et al., 2019b). Moreover, finite process constraints and qualitative methods are used, making it impossible to apply the approaches in the case of the railway (Jain et al., 2019a).

To conclude the literature research, resilience is focussed on networks, and not directly on operation processes. There are no papers referring to multi parameter analysis for assessing performance. Moreover, the analysis of interdependent systems is limited to one dimensional performance functions (Zhang et al., 2018). The ordering of terms related to resilience can be seen to be the next helpful effect.

Therefore, the aim of this paper is to organize terms related to resilience and to propose a multi properties performance function for railway resilience quantification.

### 3. Resilience concepts

The basic terms related to system and process evaluation in relation to unwanted events are often mixed and used synonymously. To minimize confusion, Figure 1 shows a presentation of the most important qualities. Reliability is the ability of a system to meet requirements in a specified time interval, with no damages or failures related to the system's components (Birolini, 2017). Dependability is a wider quality. It is defined as the system's ability to perform all tasks, and to fulfil all requirements correctly in a given time interval. It means that damages to system components may occur, but the system outcome will be kept (Birolini, 2017). Both qualities make the assumption of system operation under certain conditions.

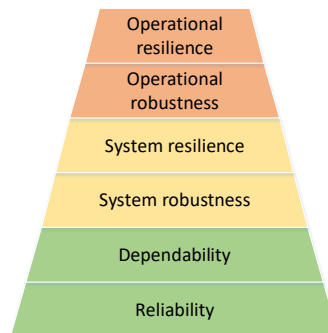


Fig. 1. Qualities describing the system in terms of unwanted events

Looking at the literature, robustness is defined as the ability to withstand shocks that influence the system (Salido et al., 2008). On the other hand, resilience is defined as the ability to recover the system in a given time period after unwanted events and their consequences (Liu and Song, 2020). As can be seen in Figure 1, this contribution proposes another approach, which divides the mentioned qualities into system and process ones. Therefore, system robustness will be defined as the ability of the system to withstand unwanted events and their consequences and to not turn into an unavailability state.

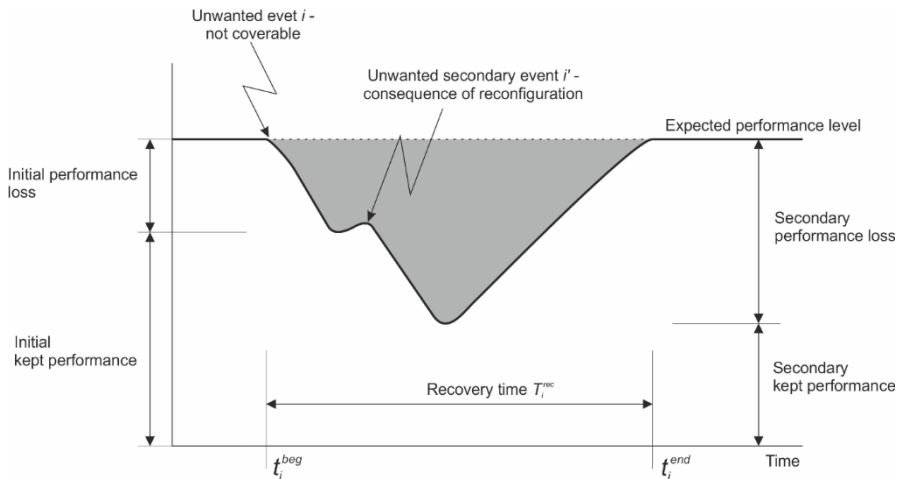


Fig. 2. Robustness and resilience concept

This is given for a specified time interval. The difference to reliability or dependability is that in the case of system robustness the conditions may change, and the operational parameters may exceed the assumed critical limits. Events that change the conditions dramatically, apart from the assumed certain ones, will be called shocks.

System resilience will be understood as the ability of the system to recover from disruptions in a given time period. It refers to major events that cause full or partial system unavailability. In this meaning, system resilience can be described using general performance measures like network capacity, available nodes etc. Operational resilience is the ability of a system to recover operation processes after they have been disrupted as a consequence of unwanted events. In terms of operational resilience, undesirable events are taken into account in terms of the outcome of the operation process. Therefore, if an unavailability situation has no influence on the operation process, it is not important in terms of operational resilience.

The recovery of operation processes can be implemented by reconfiguration actions like: the re-ordering, re-timing or re-routing of trains (D'Ariano, 2010, Corman et al., 2010, Jacyna-Golda et al., 2017a, Jacyna-Golda et al., 2017b). The literature review shows that further system consequences are not taken into account in detail for recovery actions. Nevertheless, the issue of further disruptions caused

by earlier decisions is a key issue in resilience research. Figure 2 shows a concept of performance loss, recovery and further disruptions in relation to the investigation of resilience.

The information presented in Figure 2 is held on a general level. Therefore, resilience and robustness can be understood in this case as the operation and quality of the system. Performance loss, in reference to system robustness and system resilience, will not necessarily be the same as when in relation to operational variants.

#### 4. Performance qualities

According to the literature review, train re-routing, re-ordering, re-timing and connection cancelling were identified as the main variables for dispatching actions. A combined fault tree and event tree analysis was performed to find out what issues would be important for the occurrence of unwanted events that are the consequence of reconfiguration actions. The main results are shown in Figure 3.

The analysis starts with not extended events. These unwanted events may be coloured black and supplemented by a number. For the first reading from the bottom to the top the numbers are not relevant. For the second reading, the numbers mean that the given situation identified in the top of the figure (where the event tree ends) may have an influence on the occurrence of the given event in the bottom of the fault tree.

The failures rise until the top event, which is named as system unavailability. It was assumed that system unavailability is each unwanted event that results in a disruption related to the operation processes. In other words, it is not necessary that there is damage to the system components. Sufficiently for the system unavailability occurrence is any event which causes delays. If the time to repair is less than the time assigned to the given operation process, than no reconfiguration is necessary and the remaining processes will be implemented without disturbances. On the other hand, if the time margin is less than the time to repair, than there are two possibilities. Firstly, no reconfiguration actions will be implemented. If the delay is small, it can be compensated by a given number of processes in the series (train ride) without affecting other ones. Secondly, delay propagation may appear. Delay propagation in such a case is the first identified influencing factor for further delays.

If reconfiguration actions will be implemented, the final consumer can either experience consequences (transport service changes) or not (no transport service changes). For both, the implemented reconfiguration can cause further unwanted events due to:

- the reaching of limits in the train crews' working time,
- reaching limits of the vehicle interval to maintenance,
- vehicles that are inadequate for the tasks,
- inadequately prepared train crews,
- tasks outside of the daily routine.

A vicious circle may appear, and reconfigurations may lead to further disruptions, in turn making the system less stable after subsequent time steps. Therefore, a train with a schedule that is different to the expected one will be named as a reconfigured train.

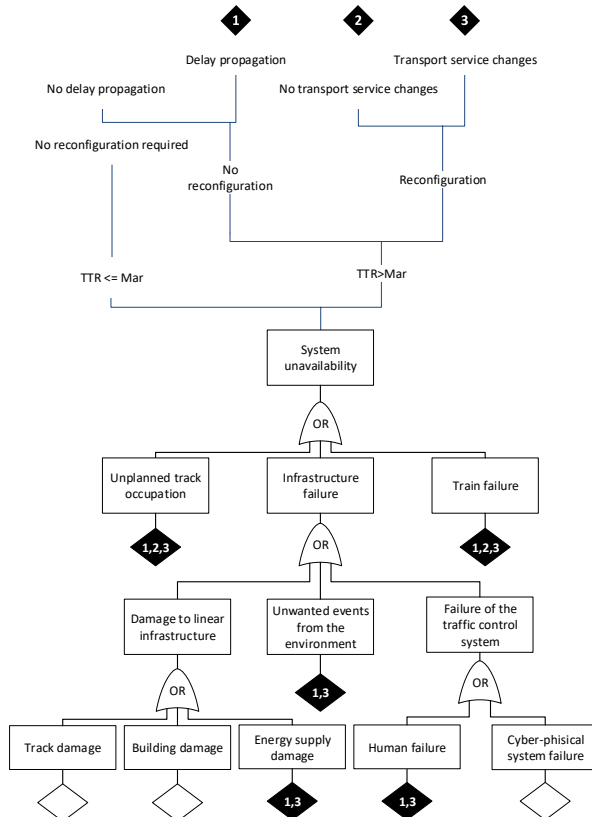


Fig. 3. The fault tree analysis combined with the event tree analysis

Reconfiguration is connected to the process of order changing, changing or cancelling of interconnections, exchanging of train crews (Golebiowski, 2020), exchanging of vehicles, and changing of tracks within a given line. It was assumed that the operation process is strictly connected to a given railway line. It follows that track changes are possible within the same railway line, with the same stops, and with the same operation points. If the railway line is changed, the scheduled process will be cancelled and a new one will be introduced into the schedule. Finally, the most useful input variables for the model were identified:

- the proportion of operation processes under implementation in opposite to cancelled ones  $\theta^l$ ,
- the proportion of not reconfigured processes  $\theta^S$ ,
- the proportion of punctual processes (in terms of the ending time)  $\theta^P$ ,
- the third quartile of operation process delays  $\theta^Q$ ,
- the ratio of the probability of no further delays for the analysed scenario to the probability of no further delays for the scheduled situation  $\theta^L$ , which is calculated until the end of the event.

The proportion of operation processes under implementation gives information about the operated nodes on the network. The proportion of not reconfigured processes gives information about correctly assigned train crews, vehicles and tracks (within the given railway line). The proportion of punctual operation processes and the third quartile of delays define the punctuality of the processes and the possibility of delay propagation. The probability of no further disruptions gives information about the possibility that the given solution will be robust to new random shocks.

## 5. Process description

The operation processes  $O$  of a system can be defined as:

$$O=A,D,E \quad (1)$$

where:

$A$  – set of all actions in the system, related to the operation process,

$D$  – set of all dependencies between actions,

$E$  – set of all unwanted events which impact on the system and the operational processes.

The set of actions can be described as:

$$A = \langle A^S, A^R \rangle \quad (2)$$

where:

$A^S$  – set of scheduled actions,

$A^R$  – set of additional actions, the occurrence of which is caused by reconfiguration decisions.

Actions change the state of the system e.g. the location of a train will change after the action of the train moving. This type of action, for the performed research, will be called the main operation process. There are also supporting processes. These are actions that directly allow the main operation processes to be implemented, e.g. issues related to the takeover of the vehicle by the train crew. In general, actions  $a_{i|l}$  are defined in the same way for scheduled and reconfigured cases:

$$a_{i|l} = \langle c_j: c_j \in C^l, t_{i|l}^{start}, t_{i|l}^{end}, \psi_m: \psi_m \in M^{i|l}, \gamma_n: \gamma_n \in \Gamma^{i|l}, \eta_u: \eta_u \in H^{i|l} \rangle \quad (3)$$

where:

$c_{j|l}$  – cluster  $j$  on network part  $l$ ,

$C^l$  – subset of clusters belonging to network part  $l$ ,

$t_{i|l}^{start}$  – starting time of action  $i$  on network part  $l$ ,

$t_{i|l}^{end}$  – ending time of action  $i$  on network part  $l$ ,

$\psi_m$  – train crew  $m$ ,

$\Psi^{i|l}$  – subset of train crews meeting the requirements of action  $i$  on network part  $l$ ,

$\gamma_n$  – vehicle  $n$ ,

$\Gamma^{i|l}$  – subset of vehicles meeting the requirements of action  $i$  on network part  $l$ ,

$\eta_u$  – passengers or cargo  $u$ ,

$H^{i|l}$  – subset of passengers or cargo meeting the requirements of action  $i$  on network part  $l$ .

A cluster is a part of the railway network, and is located between two operation control points which allow the track to be changed. The cluster is described as follows:

$$c_j = \langle pO_i^{start}, pO_i^{end}, PO_i^{int} \rangle \quad (4)$$

where:

$pO_i^{start}$  – starting point of network part  $l$ ,

$pO_i^{end}$  – ending point of network part  $l$ ,

$PO_i^{int}$  – set of intermediate operation and commercial points on network part  $l$ .

The cluster, train crew, vehicle, and passengers or cargo can be treated as the resources needed to implement the required action. A supporting action may not require all the listed resources. An example of the supporting actions is the preparation of train crews for duty. An operation process can be the source of some, or all, of the listed resources to another process. Therefore, the train crew, vehicle, infrastructure, and passenger or freight interconnection will create the set of process dependencies  $D$ . It consists of subsets  $D_{i|l}$  that are related separately to each action. A dependency can be understood as the need to finish one process in order to be able to start another one.

$$D = \langle D_{i|l} \rangle \tag{5}$$

It was assumed that a process is only dependent to one other earlier process in terms of each of the identified dependencies. Thus, a subset of dependencies for an action can consist of a maximum of four items.

$$D_{i|l} = \langle D_{i|j}^{tc}, D_{i|j}^{veh}, *d_{i|j}^{inf}, D_{i|j}^{int} \rangle \tag{6}$$

where:

$D_{i|j}^{tc}$  - set of train crew deliveries from known actions to action  $i|l$ ,

$D_{i|j}^{veh}$  - set of vehicle deliveries from known actions to action  $i|l$ ,

$*d_{i|j}^{inf}$  - the delivery of the an infrastructure part from a known action  $*$  to action  $i|l$ ,

$D_{i|j}^{int}$  - set of passenger or freight deliveries from known actions to action  $i|l$ .

There were sets of train crews, vehicles and interconnections dependencies introduced because in each case may more than one process deliver members of the train crew, vehicles or passengers to the analysed action. In terms of the infrastructure, a maximum of one action must be finished until the

analysed one can be started. All of these dependencies are time-related.

The last process parameter is the set of unwanted events. It can be described by subsets  $E^{i|l}$  of events related to action  $i|l$ .

$$E = \langle E^{i|l} \rangle \tag{7}$$

Unwanted events may be related to all the resources needed to perform action  $i$  on network part  $l$ .

### 6. Operation process evaluation model

As already stated, performance depends on a couple of issues. The identified process qualities can be characterized by the proportion of operation processes under implementation, the proportion of not reconfigured processes, the proportion of punctual processes, the third quartile of delays, the ratio of the probability of no further delays for the analysed scenario to the probability of delays within the basic schedule. These input parameters for the performance function are incoherent relative to each other. Due to different natures, they cannot be put together using the classical approach. Therefore, looking at literature examples (Kierzkowski and Kisiel, 2017, Skorupski, 2016), the fuzzy logic approach was chosen to find the performance function  $f$  while taking into account the identified issues. The fuzzy set  $A$  (alpha) will be denoted as:

$$A = \langle (\theta, \mu_A(\theta)): \theta \in \Theta, \mu_A \in [0,1] \rangle \tag{8}$$

where  $\mu_A$  is the membership function of this set.

A Mamdani fuzzy inference system was constructed (Mamdani & Assilian, 1975, Zadeh, 1973), the general model of which is shown in Figure 4. For the input of the model, unfuzzy variables  $\theta$ , estimated depending on the type of variable, are used. During the input fuzzification, the sharp variables are connected to linguistic variables.

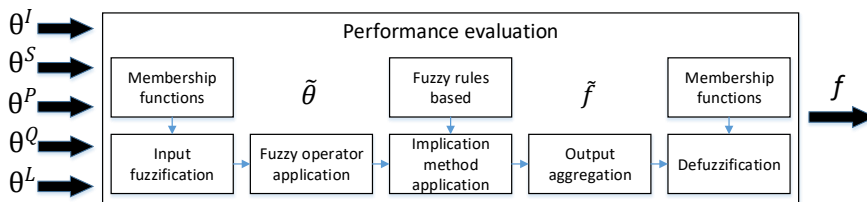


Fig. 4. Concept of the performance evaluation model.



The fuzzified values  $\tilde{\theta}$  are then input for applying the implication method, which uses the set of fuzzy rules and prerequisites to estimate the linguistic variable  $\tilde{f}$ . It is finally transformed during the defuzzification process to the outcome in form of the performance function  $f$ .

When applying the implication method, AND and OR operators are used. For the AND operator, a  $\min(*)$  function is used, while for the OR operator, the maximum function  $\max(*)$  is used.

For the input variables  $\theta$  and the output variable  $\tilde{f}$ , membership functions were established. The function shapes are shown in Figures 5 and 6. The membership functions were elaborated in cooperation with experts from the railway industry and by using the two literature reviews performed by Restel in 2014 and 2019.

The third quartile of delays  $\theta^Q$  (Figure 5a) is characterized by the linguistic variables *Good* and *Poor*. The input variable's  $\theta^Q$  domain starts at zero and is not limited to the right side. The value is calculated for the process data, taking into account only the non-zero delays.

According to the literature survey shown in (Restel, 2014), the acceptable delay level varies from 2.5 minutes up to 5 minutes. A delay between 5 and 15 minutes can sometimes be accepted, but delays higher than 20 minutes are not acceptable.

The proportion  $\theta^L$  of no further delays for the actual situation related to the scheduled situation is calculated using the following formula:

$$\theta^L = \frac{\prod_{c=1}^d (1 - p_c^{act})}{\prod_{c=1}^d (1 - p_c^{sch})} \quad (9)$$

where:

$c$  - the given pair of dependent processes,

$d$  - number of dependent process pairs until the end of the disruption,

$p_c^{sch}$  - probability of disruption propagation for process pair  $c$  according to the theoretical schedule,

$p_c^{act}$  - probability of disruption propagation for process pair  $c$  according to the actual schedule.

The input variable  $\theta^L$  is characterized by the linguistic variables *Good* and *Poor*. Its lower domain border is zero, while its upper border is theoretically not limited. Nevertheless, the possibility that a new-made schedule would be better than the theoretical one is quiet low. Therefore, the expected values

should be lower than one. The concept of such disruption propagation probability quantification was explained by Friedrich et al. (2019).

The proportion of scheduled processes under implementation  $\theta^I$  (Figure 5c) is characterized on its domain  $[0,1]$  by the variables *Good* and *Poor*. The proportion of punctual processes  $\theta^P$  (Figure 5e), as well as the proportion of not reconfigured processes  $\theta^S$  (Figure 5d), are both described by three linguistic variables on their domains  $[0,1]$ . Additionally to *Good* and *Poor*, the variable *Intermediate* has also been introduced.

The output variable performance was settled by a range from zero to one. One means that there are no disruptions, and that the system is operated within the schedule. For the output variable, nine membership functions were established (Figure 6).

For applying the implication method, fifty nine rules were established. There is no difference in the weight of the rules. For all rules, according to the input membership functions, the output membership function values are calculated as  $\mu_{out}^{R1}(z), \mu_{out}^{R2}(z), \dots, \mu_{out}^{R59}(z)$ . During the implication step, the minimum function value was used, while during the output aggregation, the maximum function was used.

Finally, the defuzzification process is implemented based on the centroid estimation.

$$z^* = \frac{\int \mu_{out}(z) \cdot z dz}{\int \mu_{out}(z) dz} \quad (10)$$

The described performance evaluation model was implemented in MATLAB software.

## 7. Case study

Figure 7 shows a theoretical, graphical timetable for an existing railway line in Poland. It is double tracked. There are express trains marked in red, and black regional trains and freight trains marked in grey. There are some branches to other lines, where trains enter or leave the analysed line, but there is no possibility to reroute the trains, except on the neighbouring track.

It was assumed that damage occurred on one of the tracks between nodes B and C at 19:35, which lasted for two hours (marked as a violet arrow). The simplest dispatching strategy was implemented – the train order was not changed, and all trains moved one after the other on the available track. For each

minute, the number of processes (train moving on the track) in the system, the number of delayed processes, the number of reconfigured processes (moving on the wrong track), the delays, and the remaining dependencies (until the end of disruption) were estimated. Using the data, the input variable values were calculated.

It was found, that for all trains the delay probability distributions on the analysed sections are quiet similar. The sections belong to the Lower Silesian railway network, but cannot be named directly due a

confidentiality agreement. The punctual arrival probability is about 0.949. The remaining 0.051 can be described by the lognormal distribution LN(2.2552;0.8783), as shown in Figure 8. It was estimated for this railway line basing on operational data from the Polish Infrastructure Manager from the years 2009-2011. More than six hundred unwanted events have been registered, that influenced 1208 from 23686 analysed train rides. The distribution parameters were proven by Chi-squared test at significance level 0.05.

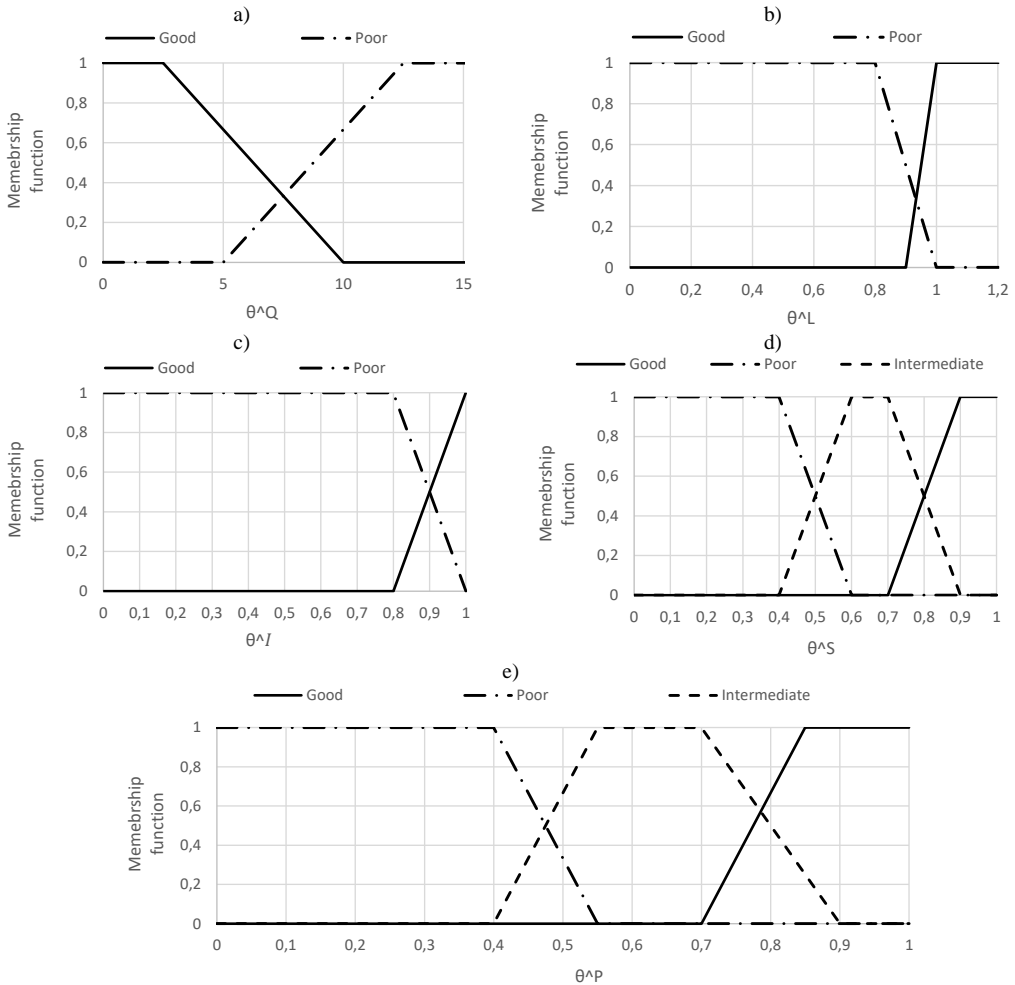


Fig. 5. Membership functions for the input and linguistic variables: a) third quartile of delays, b) ratio of the probability of no further scheduled/actual delay , c) proportion of processes under implementation, d) proportion of no reconfigured processes, e) proportion of punctual implemented processes.

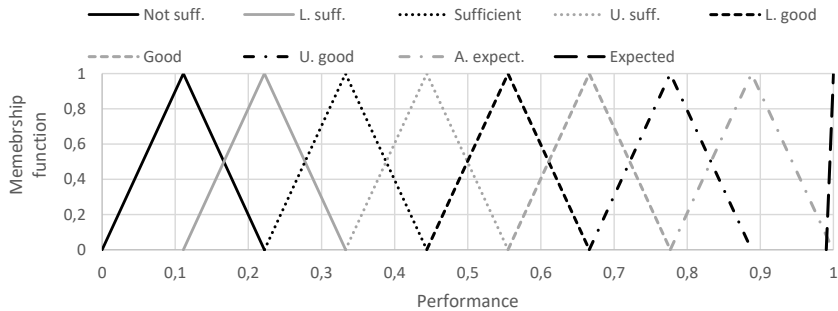


Figure 6. Membership functions for the output variable and linguistic variables.

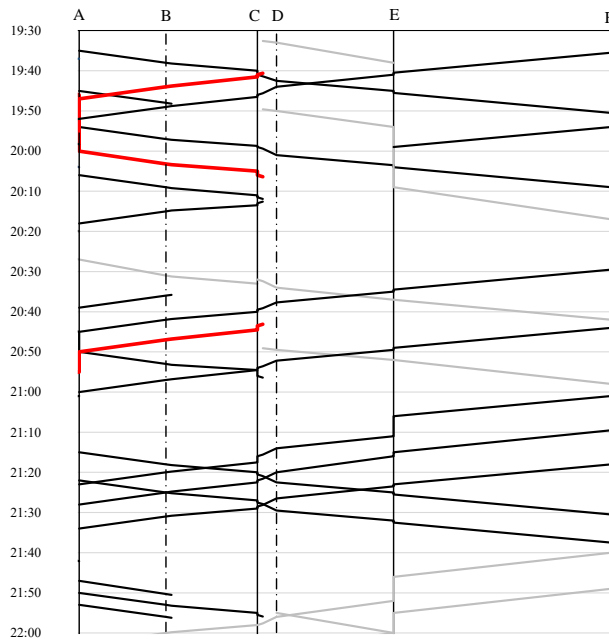


Fig. 7. Example of an operation situation related to a real timetable.

All input variables were paired with the time axis. Using the database, the fuzzy operation performance function was computed in Matlab software. The results are shown in Figure 9.

Additionally to the performance curve, two individual performance measures that were used in the literature were also presented – the proportion of delayed and the proportion of available node connections in the analysed system.

As can be seen, the node connections indicator is static, and not related to the performed processes.

Close to that will be all indicators related to maximum flow capacity. Thus, such parameters are not good enough for a system like the railway, because dynamical process issues are not taken into account. On the other hand, taking only one dynamical indicator, such as the proportion of delayed processes, will be strong and the gathered perception of the situation will be distorted.

It can also be seen that both the dynamical and static issues are covered by the proposed approach, and it can therefore be seen to be a new promising tool for evaluating operation processes.

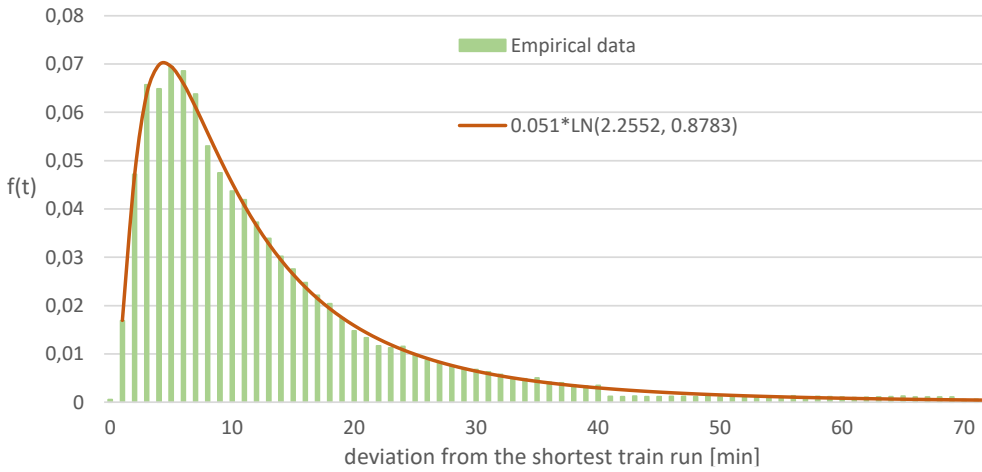


Fig. 8. Probability distribution of time deviations from the shortest train run for a chosen Polish railway line.

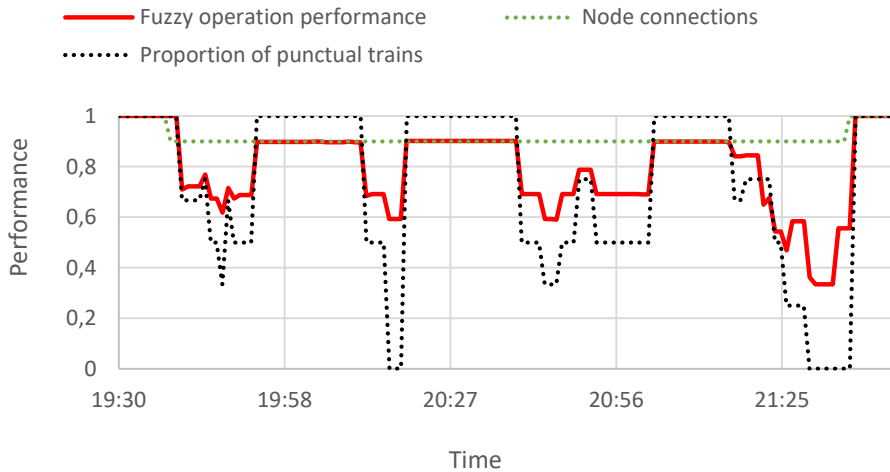


Fig. 9. Performance evaluation for disrupted railway operation processes.

### 8. Conclusions

The introduced concept of operational resilience and operational robustness allows the ordering of issues related to system reliability, robustness and resilience research. It opens a new view on evaluating the system after unwanted events, especially in terms of complex socio-technical systems with operational process dependencies. The proposed concept makes it possible to perform a more structured evaluation of systems and processes. Thus, recovery after unwanted events will be more efficient and the safety of the system will increase.

Secondly, as a result of this research, operational issues influencing the occurrence of failure were identified. It was found that the recovery process can initiate further unwanted events, and therefore destabilize the operation processes. Therefore, particular attention must be paid to process dependencies, which were identified as vehicle and train crew rotations, track occupation, and the interconnections of passengers or freight.

The incoherent process parameters could hardly be put together for one multi-criterial approach. For this reason, the fuzzy approach, taking into account these

parameters, was used to identify the performance curve. The elaborated fuzzy model is based on the knowledge of collected literature, expert knowledge, and the performed operational research. The method allows the typical resilience problem to be combined with the typical dispatching problem. According to the case study, it can be seen that the fuzzy model includes both approaches. The results are promising and further research is planned.

For the future it is assumed that the introduced operational variants of resilience and robustness will be investigated more deeply. Moreover, their quantification, based on actual results, will also be performed. Finally, optimization issues will be taken into account to support the planning and implementing phases of operational schedules.

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